

~~CONFIDENTIAL~~  
X-615-64-103

NG5-35264

TM X-55036

# THE TEMPERATURE OF CHARGED PARTICLES IN THE UPPER ATMOSPHERE

BY  
R. E. BOURDEAU

MAY 1964



— GODDARD SPACE FLIGHT CENTER —  
GREENBELT, MARYLAND

COSPAR, May 1964

THE TEMPERATURE OF CHARGED PARTICLES IN THE UPPER ATMOSPHERE

by

R. E. Bourdeau  
NASA-Goddard Space Flight Center  
Greenbelt, Maryland

COSPAR  
May, 1964

# THE TEMPERATURE OF CHARGED PARTICLES IN THE UPPER ATMOSPHERE

by

R. E. Bourdeau  
NASA-Goddard Space Flight Center  
Greenbelt, Maryland

## ABSTRACT

Three general methods of investigating charged particle temperatures in the upper atmosphere have been used: (a) direct measurements from rockets and satellites; (b) indirect determination using electron scale heights measured from rockets and satellites; (c) ground-based radar incoherent backscatter experiments. The latitude, altitude and temporal trends of these results are reviewed and the implications discussed.

Observations by all three methods are consistent in showing that the electron temperature increases with latitude for both daytime and nighttime conditions. Moderate differences between the daytime electron and neutral gas temperatures are indicated to altitudes well above the F2 peak for a winter mid-latitude ionosphere at an epoch between solar maximum and solar minimum conditions. Much larger daytime differences are observed for summer months and for solar minimum conditions. All of these trends reflect corresponding changes in the electron density.

The daytime observations are consistent with ultraviolet radiation as the predominant heat source if the possibility of photoelectrons diffusing along magnetic field lines and depositing their excess energy elsewhere is included. A nighttime heat source small compared to the daytime ultraviolet effect is required to explain the observations.

## INTRODUCTION

At the first Florence meeting of COSPAR, early direct measurements of electron temperature  $T_e$  were reported from rockets (Aono et al, 1961) and from the Explorer VIII Satellite (Bourdeau, 1961). The Japanese rocket results suggested temperature equilibrium between electrons and neutral constituents in the E region of the daytime ionosphere. Low values of  $T_e$  in the daytime E region subsequently were confirmed by US rocket experiments (Spencer et al, 1962). However, other rocket  $T_e$  measurements (Smith, 1961; Aono et al, 1962; Brace et al, 1963) showed that significant departures from temperature equilibrium are more often observed than not in the E region even at night. The results of Spencer et al (1962) showed that departures from temperature equilibrium extended well into the daytime F region.

Early measurements of charged particle temperatures applicable to the region considerably above the F2 peak at mid-latitudes for solar conditions when the 10.7 cm flux index ( $S_{10.7}$ ) was  $150 \text{ WM}^{-2} \text{ CPS}^{-1}$  were reviewed by Bauer and Bourdeau (1962) and Bourdeau (1963). Implications of temperature equilibrium at high altitudes which they optimistically derived from the data critically depended on the assumed neutral gas temperature ( $T_g$ ). When these early direct measurements of  $T_e$  and of the average electron-ion temperature ( $\frac{T_e + T_i}{2}$ ) obtained from electron density profiles now are compared with more recent reference atmospheres moderate values for  $T_e/T_g$  of about 1.3 are indicated at midday even to altitudes above 1000 km for the indicated level of solar activity. These observations are in approximate agreement with the theoretical model of Hanson (1962) who assumed electron density values close to these particular observational conditions.

More extensive charged particle temperature observations for different epochs of the solar cycle now have been made by use of ground-based radar incoherent backscatter experiments, by additional direct measurements from rockets and satellites and indirectly from electron density profiles obtained from rockets and the Alouette Topside Sounder Satellite. In general, the trend is toward much larger departures from temperature equilibrium than indicated in the theoretical models and in the earlier observations especially at the higher altitudes.

It is timely then, as is done in this report, to compare these trends with the introduction of latitude and temporal electron density variations in the early theoretical models.

#### FACTORS CONTROLLING THE ELECTRON TEMPERATURE

The principal factors controlling  $T_e$  are:

##### Heat Input

1. Solar Ultraviolet Radiation
  - A. Locally-deposited energy
  - B. Diffusing photoelectrons  
( $Z > 300\text{km}$ )
2. Corpuscular Radiation

##### Heat Loss

1. Inelastic collisions with neutral constituents ( $Z < 250\text{km}$ )
2. Elastic collisions with ions  
( $Z > 250 \text{ km}$ )
  - A. Ion temperature controlled only by neutral constituents
  - B. Ion temperature also controlled by electrons ( $Z > 600\text{km}$ )

### 3. Coulomb collisions of photoelectrons with ambient electrons

Thermal conductivity in the electron gas  
( $Z > 600\text{km}$ )

Theoretical charged particle temperature models based on solar ultraviolet heating alone have been developed by Hanson and Johnson (1961), Hanson (1962) and Dalgarno et al (1962). Of these, Hanson's model is the most complete in that he introduced the possibility of (a) photoelectrons diffusing along magnetic field lines and depositing their energy elsewhere, (b) the loss of ion temperature control by the neutral constituents and (c) the importance of thermal conductivity in the electron gas at high altitudes. The indicated altitudes where these factors are important represent Hanson's estimates based on his assumed model atmosphere and electron density profile.

The models of Hanson and of Dalgarno et al each used a single electron density profile and both depended on rocket measurements of ultraviolet radiation intensity (Hall et al, 1962) to estimate the heat input,  $Q$ . The EUV intensity used applies to a level of solar activity corresponding to  $S_{10.7} \approx 100$ . The heat input is the product of the EUV intensity, the ionization cross-sections and the density of the ionizable constituents and of the heating efficiency. Both theoretical charged particle temperature models exhibit approximately the same altitude behavior wherein low values of  $T_e/T_g$  are indicated in the E region, with the ratio reaching a maximum of about 2.0 - 2.5 at 200 km and decreasing in the upper F region. A principal and important difference is that the model of Dalgarno et al has  $T_e - T_g$  essentially vanishing above 300 km where Hanson's model permits values for  $T_e/T_g$  of about 1.2 constant at extremely

high altitudes.

Because the observational evidence is most heavily weighted for altitudes above the F2 peak, the most important effect to examine is the efficiency of cooling to positive ions. On the assumption that cooling occurs only by elastic collisions to atomic oxygen ions, the electron temperature is given (Hanson, 1962) by:

$$\frac{T_e - T_i}{T_e^{3/2}} \approx \frac{2.1 \times 10^6 Q}{N_e^2} \quad (1)$$

where  $Q$  is the heat input to the electrons expressed in  $\text{ev cm}^{-3} \text{sec}^{-1}$  and  $N_e$  is the electron density. For values of  $Q$  greater than a critical value ( $Q_c$ ) given by

$$Q_c \approx 2 \times 10^{-7} N_e^2 T_i^{-1/2}, \quad (2)$$

there is no solution to (1) and  $T_e$  is not limited by energy transfer to positive ions (Hanson and Johnson, 1961). If  $Q = Q_c$ ,  $T_e > 2T_i$  and if  $Q \gg Q_c$ , very large "runaway" values of  $T_e$  will result and heat conduction in the electron gas is an important effect.

#### SOLAR CYCLE VARIATIONS OF $T_e$

In Figure 1 are illustrated daytime mid-latitude electron density profiles typical of December 1960 and 1962, respectively. The principal differences to note are the much higher values of  $N_{\text{max}}$  and  $h_{\text{max}}$  for the 1960 period, and the constant electron

scale height for the 1960 case in contrast to the continually varying scale height for the 1962 profile. The monthly mean of the solar 10.7 cm flux during December 1960 was  $150 \text{ WM}^{-2} \text{CPS}^{-1}$ .

In Figure 2 is presented the mid-latitude diurnal electron temperature variation directly measured during November-December 1960 (Bourdeau and Donley, 1963) from the Explorer VIII Satellite for magnetically-quiet days assuming  $T_e$  is constant with altitude. Depending on which of the current reference atmospheres for the pertinent level of solar activity is used, the average midday  $T_e$  value of  $1600^\circ \text{K}$  taken at midday and at altitudes above 1000 km corresponds to an estimated value for  $T_e/T_g$  of about 1.15 - 1.33.

It is seen from Equation (1) that the ratio of the heat input to the square of the electron density ( $Q/N_e^2$ ) controls the electron temperature at high altitudes. The value for  $Q/N_e^2$  computed at 400 km from the December 1960  $N_e$  profile in Figure 1 closely corresponds to the value used by Hanson as an upper limit in his model. We have taken into account that the heat input  $Q$  would be larger than in Hanson's case by assuming a linear change of EUV intensity with the decimetric flux index,  $S_{10.7}$ , and a corresponding change in the density of the ionizable constituent,  $n(0)$ . The higher heat input is compensated for largely by the higher electron density than that used by Hanson. Thus we should and do estimate similar values for  $T_e$  as did Hanson. Consequently, we find excellent agreement between the observed  $T_e/T_g$  of 1.15 - 1.33 and Hanson's theoretical upper limit of about 1.15.

In Figure 3, the Explorer VIII data are included with measurements of  $(T_e + T_i)/2$  computed from early rocket  $N_e$  profiles on the assumption of diffusive equilibrium. Of particular interest is the ion density profile obtained by Hale (1961) at midday and at about the same time as the Explorer VIII obser-



vations. Here a value for  $(T_e + T_i)/2$  of  $1600^\circ\text{K}$  (Hanson, 1962b) is derived for the region above 1000 km. The data are too sparse for a firm conclusion but there is a suggestion by the inter-comparison that for winter midday mid-solar cycle conditions  $T_e \approx T_i$  at altitudes above 1000 km but that both the electron and ion temperatures are moderately higher than the neutral gas temperature. This would be consistent with Hanson's arguments that above 600 km (a) thermal conductivity of the electron gas could support differences between  $T_e$  and  $T_g$  which are constant with altitude and furthermore, (b) that the electrons rather than the neutral constituents could control the ion temperature so that  $T_i > T_g$ .

Low midday values of  $T_e/T_g$  at high altitudes also can be implied from the measurement in December 1961 of a value for  $(T_e + T_i)/2$  of  $1235^\circ\text{K}$  (Taylor et al, 1963) from a rocket flight for which an equivalent ion temperature has been inferred (Bauer, 1964). However, we emphasize here Equation (1) and the extreme sensitivity of  $T_e$  to the electron density. We further emphasize that in the actual case, ratios of  $Q/N_e^2$  which permit only moderate rather than large midday departures from temperature equilibrium as is indicated for December 1960 at high altitudes perhaps represent the exception rather than the rule at middle and high latitudes.

Let us consider now the drastic changes in charged particle temperature characteristics as one moves closer to solar minimum conditions. The average value for the index (S) of solar activity corresponding to the December 1962 profile illustrated in Figure 1 was 85. Taking into account a linear decrease in EUV intensity from the time of the rocket EUV measurements (Hall et al, 1962) and a corresponding decrease in the density of the ionizable

constituents and computing  $Q_c$  directly from the observed  $N_e$  profile, the estimated ratio  $Q/Q_c$  is larger than 2. Because of the uncertainties in our knowledge of ionization cross-sections and model atmospheres, the computation of  $Q/Q_c$  is suggestive rather than quantitative. Within these uncertainties, it does appear that the EUV effect for low electron densities is sufficient to cause very large electron and possibly runaway electron temperatures.

In Figure 4 is plotted a mid-latitude diurnal variation of electron scale heights calculated for an altitude of 500 km from electron density profiles obtained by the use of the Alouette satellite during the period October-December 1962 (Bauer and Blumle, 1964). It is seen that on the assumption of diffusive equilibrium and  $O^+$  as the principal ionic constituent, values for  $(T_e + T_i)/2$  of  $1500^\circ K$  are indicated at midday. Assuming  $T_i = T_g$ , a value for  $T_e/T_g$  of about 2.0 is indicated (Bauer and Blumle, 1964), which is much in excess of the December 1960 value. This should not be surprising because of the large increase in the ratio  $Q/N_e^2$  at 400 km and above from December 1962 to December 1960.

If the assumed model atmosphere and ionization cross-sections on which the computation of  $Q/Q_c$  depends are correct, the fact that runaway electron temperatures are not observed suggests that much of the heat input is not deposited locally. Also it should be emphasized that the ratio of 2.0 for  $T_e/T_g$  must be considered an upper limit since it assumes that at 500 km the ion and neutral gas temperatures are the same. Evans (1964) with radar-back-scatter experiments observes at similar latitudes and under similar conditions that  $T_i > T_g$  even as low as 400 km. Thus the values for  $T_e$  implied from Figure 4 may indeed be somewhat

overestimated. That the electron temperature begins to control the ion temperature at an altitude lower than that estimated by Hanson is explainable on the basis that the scale heights illustrated in Figure 4 were measured for a different model atmosphere and electron density profile than that assumed by Hanson.

In summary, the observational evidence as expected shows a large increase in  $T_e/T_g$  between December 1960 and December 1962 which corresponds to a change in the ratio of the heat input to the square of the electron density. In the 1962 case, there still appears to be a sufficient EUV flux to explain the high daytime electron temperatures observed at 500 km during periods of low electron density. There is indirect evidence that some of the energy is not locally deposited and direct evidence from Evans' results that the ion as well as the electron temperature is raised above the neutral gas temperature.

#### SEASONAL VARIATION OF $T_e$

Ionosonde data have shown that the electron density is much higher at the F2 peak in winter than it is in summer. For example,  $N_{\max}$  measured at Washington, D. C., was on the average more than a factor of two larger in the summer than in the winter of 1962. Corresponding changes in  $S_{10.7}$ , which reflect changes in the heat input are not observed. These factors are in the direction of making the ratio  $Q/N_e^2$  much higher in the summer than in the winter months. Consequently, it is possible that, at least for mid-latitudes in the Northern Hemisphere, high ratios of  $T_e/T_g$  will persist high into the upper F region throughout a solar cycle. This could explain why some of the early rocket results taken between solar maximum and solar minimum conditions (cf Spencer et al, 1962) show different electron

temperature behavior.

#### DIURNAL VARIATION OF ELECTRON TEMPERATURE

As illustrated in Figure 2, the Explorer VIII satellite results suggest a significant increase in  $T_e$  during the early morning hours. High values of  $T_e$  in the early morning at the F2 peak are also indicated in ground-based backscatter observations (Bowles et al, 1962) and at higher altitudes by Evans (1964).

Early morning maxima in electron temperature have been confirmed by use of the Explorer XVII satellite from which the maximum value of  $T_e$  is placed near 9h local time (Brace et al, 1964). The electron scale height results from Figure 4 also suggest a maximum  $T_e$  at approximately the same local time (Bauer and Blumle, 1964). Here the high scale heights for nighttime conditions reflect the importance of light ionic constituents. However, for daytime conditions it would be expected that  $m_i$  is relatively constant and thus that the early morning maximum represents a true  $T_e$  maximum. It should be pointed out that the nature and existence of an early morning peak in  $T_e$  has not been emphasized in the Ariel satellite results (Willmore et al, 1963).

It is possible to show from ionosonde data and Equation (1) on the assumption of no EUV absorption above 300 km that the ratio  $Q/N_e^2$  which controls  $T_e$  near the F2 peak maximizes at dawn. However, at high solar zenith angles there could be enough absorption above 300 km to shift the  $T_e$  maximum to later in the morning. This reasoning would insert a latitude and altitude dependence on the time of the diurnal  $T_e$  maximum. It would be expected that the effect becomes more diffuse at higher altitudes because here the diurnal amplitude of the ionizable constituent has increased relative to the amplitude of the diurnal  $N_e$  variation (Bourdeau

and Donley, 1963).

#### LATITUDE VARIATION OF ELECTRON TEMPERATURE

Early ionosonde data showed that the daytime electron density at the F2 maximum increases drastically as one goes from mid-latitudes toward the geomagnetic equator. More recently, results from the satellite Alouette has extended the observation that the geomagnetic field plays an important role in governing the electron density distribution to altitudes well above the F2 peak. In Figure 5 is presented an idealized representation of the latitudinal behavior of  $N_e$  prepared by Jackson (private communication) by combining topside sounder (Lockwood and Nelms, 1963) and ionosonde (Wright, 1962) results. Other Alouette data (King et al, 1963) show that the equatorial anomaly builds up earlier in the day at the eastern longitudes. It should be clear from the illustration and Equation (1), that in the daytime  $T_e$  should increase with increasing latitude on the basis of the electron density behavior alone, if we assume no EUV absorption above 300 km and no latitude dependence of the neutral gas characteristics. An increase of daytime electron temperatures with latitude is indicated by all three methods of charged particle temperature investigation for altitudes below about 800 km. Alouette satellite data suggest constant electron scale heights above 800 km (King et al, 1963).

The ground-based incoherent backscatter results at the geomagnetic equator (Bowles, 1963) show that in the region 200-350 km  $T_e/T_i$  is close to 2 during the daytime hours, maximizing at about 275 km. Above about 400 km in the daytime the results show that  $T_e/T_i$  is unity. Daytime ion temperatures (Bowles, private communication) for March 1964, in the vicinity of  $1000^{\circ}\text{K}$  are observed. Depending on the adequacy of the Harris-Priester reference

atmosphere, this would put an upper limit on  $T_e/T_g$  of 1.2 even during solar minimum conditions. Low values for  $T_e/T_g$  at high altitudes would be expected near the geomagnetic equator because of the generally higher values of  $N_e$  and because near this location diffusion of photoelectrons vertically tends to be inhibited. This supposes heating only by EUV radiation.

The incoherent backscatter results of Evans (1962, 1964) taken near  $50^\circ$  north magnetic latitude show drastically different behavior of charged particle temperatures. This would be expected because of (a) the generally lower value of  $N_e$  than would exist at the equator, and the higher probability of (b) the photoelectron diffusion effect and (c) additional sources of ionization. The earlier results of Evans' taken in March-April 1962, show daytime ratios of  $T_e/T_i$  of up to 1.6 in the 300-400 km and that  $T_e$  increases with altitude up to 700 km (Evans, 1962). In more recent results taken during July 1963, Evans (1964) offers two possible interpretations for his daytime data obtained for altitudes up to 700 km: (a) if the ionic constituent is all  $O^+$ ,  $T_e$  and  $T_i$  continually increase with altitude to values of  $2320^\circ K$  and  $2040^\circ K$  at approximately 700 km or (b) assuming a mixture of 80 percent  $O^+$  and 20 percent  $He^+$  at 700 km,  $T_e$  maximizes at about 450 km then decreases to  $1960^\circ K$  at 700 km while  $T_i$  increases to a value of  $1410^\circ K$  at 700 km. The trend of ion composition results (Hanson, 1962; Bourdeau et al, 1962; Bowen et al, 1963; Gringauz et al, 1963; Taylor et al, 1963) would imply that the latter alternative is the more likely. If so, it would be consistent with high values of  $Q/N_e^2$  permitting high values of  $T_e$  especially below 450 km, and the possibility that cooling to light ionic constituents is becoming effective above 450 km. It should be noted that Equation (1) applies only for  $O^+$  and that

the cooling efficiency to ions should be inversely proportional to the ionic mass,  $m_i$ .

Direct electron temperature measurements measured with the use of the Ariel satellite also show that  $T_e$  significantly increases with latitude (Willmore et al, 1963) the steepest gradient centered at a geomagnetic latitude of about  $20^\circ$ . The midday  $T_e$  value given at the geomagnetic equator for an altitude of 400 km is about  $900^\circ\text{K}$  which compares favorably with  $T_g$  given by Harris-Priester for the pertinent level of solar activity and with the  $T_i$  measurements of Bowles. The trend of the latitude variation at 400 km from the Ariel satellite is generally consistent with the latitude variation  $N_e$  and thus both the ground-based results of Bowles and of Evans (Willmore et al, 1963).

However, the situation above 400 km is more complicated. The Ariel results show  $T_e$  increasing with altitude up to maximum height of the observations at all latitudes. The continuing increase with altitude of  $T_e$  from Ariel at higher latitudes would be consistent with the 1962 results of Evans but not for the likely possibility which Evans offers that  $T_e$  decreases above 450 km for his 1963 results. We suffer here in the comparison from a lack of simultaneity in the observations. An increase of  $T_e$  at all altitudes in 1962 is perhaps reconcilable with a possible decrease in  $T_e$  above 450 km in 1963 on the base of a lowering with solar activity of the  $O^+ - He^+$  transition altitude.

The fate of the photoelectrons which apparently escape from the altitude of their formation is not yet clear. We have made a case that for the December 1962 mid-latitude profile the ratio of  $Q/Q_c$  possibly is large enough that the high values of  $T_e$  observed up to 500 km at mid-latitudes could be explained on the basis of the EUV effect and heat conduction in the electron gas.

In his interpretation of the daytime altitude behavior of  $T_e$  from the Ariel satellite, Willmore (1963) finds that for altitudes up to 600 km, the altitude dependence of the heat input computed from the observed  $T_e$  and  $N_e$  (cf Equation 1) follows the scale height of atomic oxygen and thus also concludes that the main energy input below 600 km is by the photoionization of atomic oxygen. He additionally finds that the increase of  $T_e$  above 800 km can be explained by additional energy input from the photoelectrons diffusing from below together with the main energy loss mechanism being thermal conduction in the electron gas rather than collisions with positive ions. His conclusions assume that the photoionization of helium is unimportant and additionally depend on an assumed model atmosphere.

#### NIGHTTIME CHARGED PARTICLE TEMPERATURE MEASUREMENTS

The charged particle temperature measurements of Figures 2 and 3 are too sparse and the dependency on the assumed reference atmosphere too critical to draw firm conclusions about departures from temperature equilibrium at night for mid-solar cycle conditions. Bowles et al (1962) observe that  $T_e/T_i$  is unity at night at the geomagnetic equator with  $T_i \cong 600^\circ\text{K}$ , the latter value being in fair agreement with the Harris-Priester reference atmosphere. Remembering the different altitudes and times of the observations, Willmore et al (1963) report that at 1000 km midnight values of  $T_e$  increases from about  $800^\circ\text{K}$  at the equator to  $1400^\circ\text{K}$  at  $60^\circ$  magnetic latitude. Evans (1964) indicates a small but significant departure from temperature equilibrium in the F region at  $50^\circ$  north magnetic latitude. The definite evidence from the Ariel satellite for quite significant departures from temperature equilibrium at night at medium latitudes have been confirmed by rocket measurements (Brace et al, 1963). The Ariel results show that the nighttime departure



from equilibrium becomes more pronounced at the higher latitudes. The nighttime source required to explain the Ariel observations has been estimated to be less than 30 percent of the daytime EUV heat input (Willmore, 1963).

As an example of the sensitivity of nighttime electron temperatures to small sources of heat input, consider Equation (1) and the fact that for solar minimum conditions,  $N_e$  varies by a factor of 4 from day to night at 400 km (Bauer and Blumle, 1964). From these considerations, it can be shown that less than 10 percent of the daytime EUV heat input would be required at night to maintain the same temperature difference ( $T_e - T_g$ ) throughout the day.

#### SUMMARY AND CONCLUSIONS

For all temporal conditions and latitudes, large departures from temperature equilibrium ( $T_e/T_g \geq 2$ ) are observed in the daytime lower F region at the altitude of maximum rate of electron productions. Moderate but significant daytime values for  $T_e/T_g$  are maintained to very high altitudes in winter at mid-latitudes in the middle of the solar cycle. Daytime mid-latitude data taken for summer and/or solar minimum conditions when electron densities generally are much lower reveal much larger values of  $T_e/T_g$  persisting to altitudes well above the F2 maximum. There is considerable evidence at least for altitudes below 600 km that the diurnal electron temperature maximum occurs in the early morning. Observed increases of daytime electron temperature with latitude follows the observed electron density which is under geomagnetic control. All of these temporal and latitudinal trends in the observed electron temperature are consistent with EUV as the predominant daytime source of electron heating.

The uncertainties in calculating the EUV effect make it difficult to infer other possible daytime heat sources at the present time. The charged particle temperature observations strongly suggest the possibility that not all of the EUV energy is locally deposited, an important factor to be considered in the theories of formation of the ionosphere. There is some evidence principally from back-scatter experiments that the ion temperature is controlled by electrons at very high altitudes.

Significant departures from temperature equilibrium at night have been observed especially for conditions close to solar minimum. The estimated intensity of this additional heat source increases with latitude but at all latitudes is only a fraction of the daytime EUV effect.

#### ACKNOWLEDGEMENT

The author is grateful to S. J. Bauer, L. J. Blumle, J. V. Evans and K. Bowles, for early access to the results of their charged particle temperature observations.

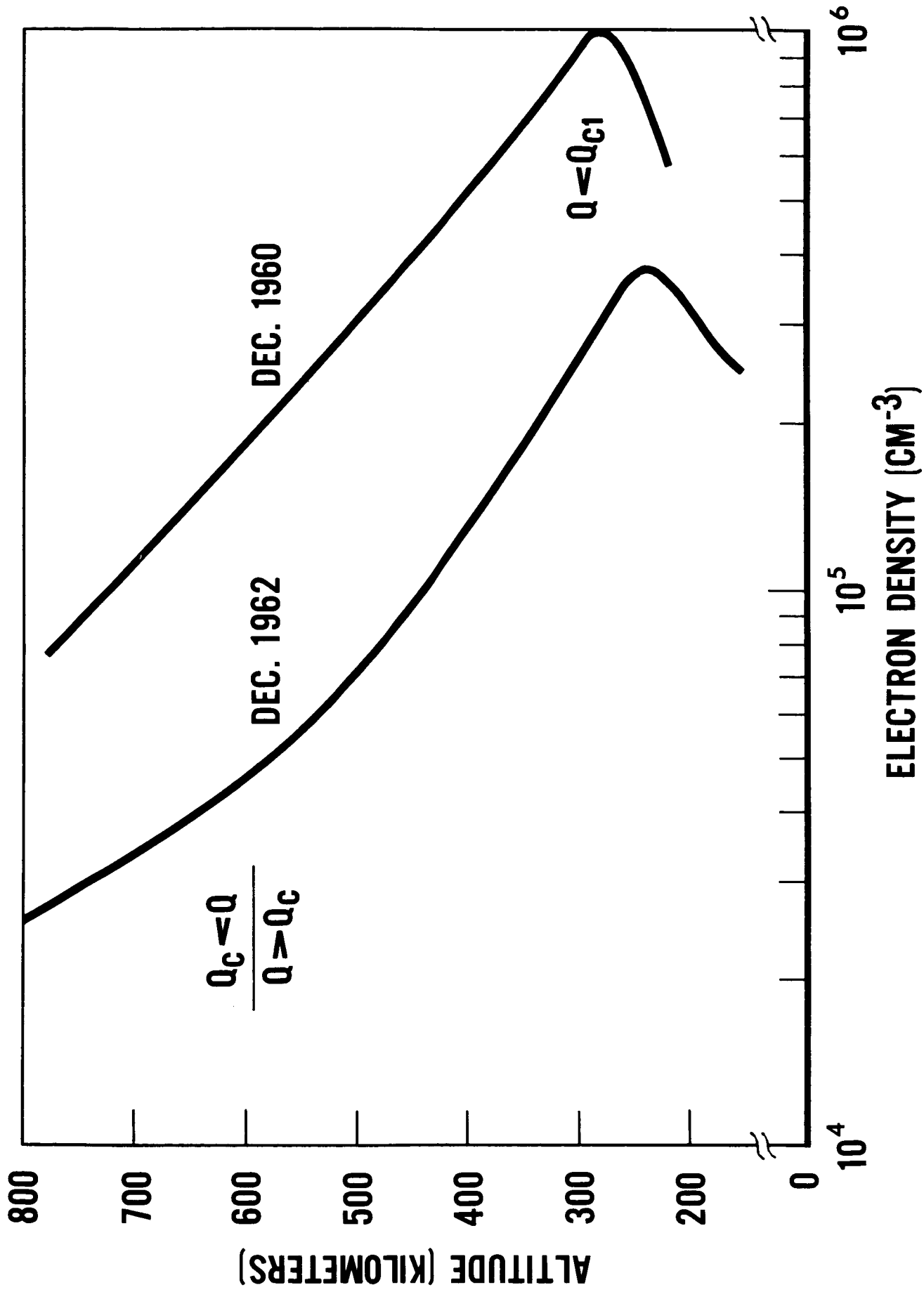
REFERENCES

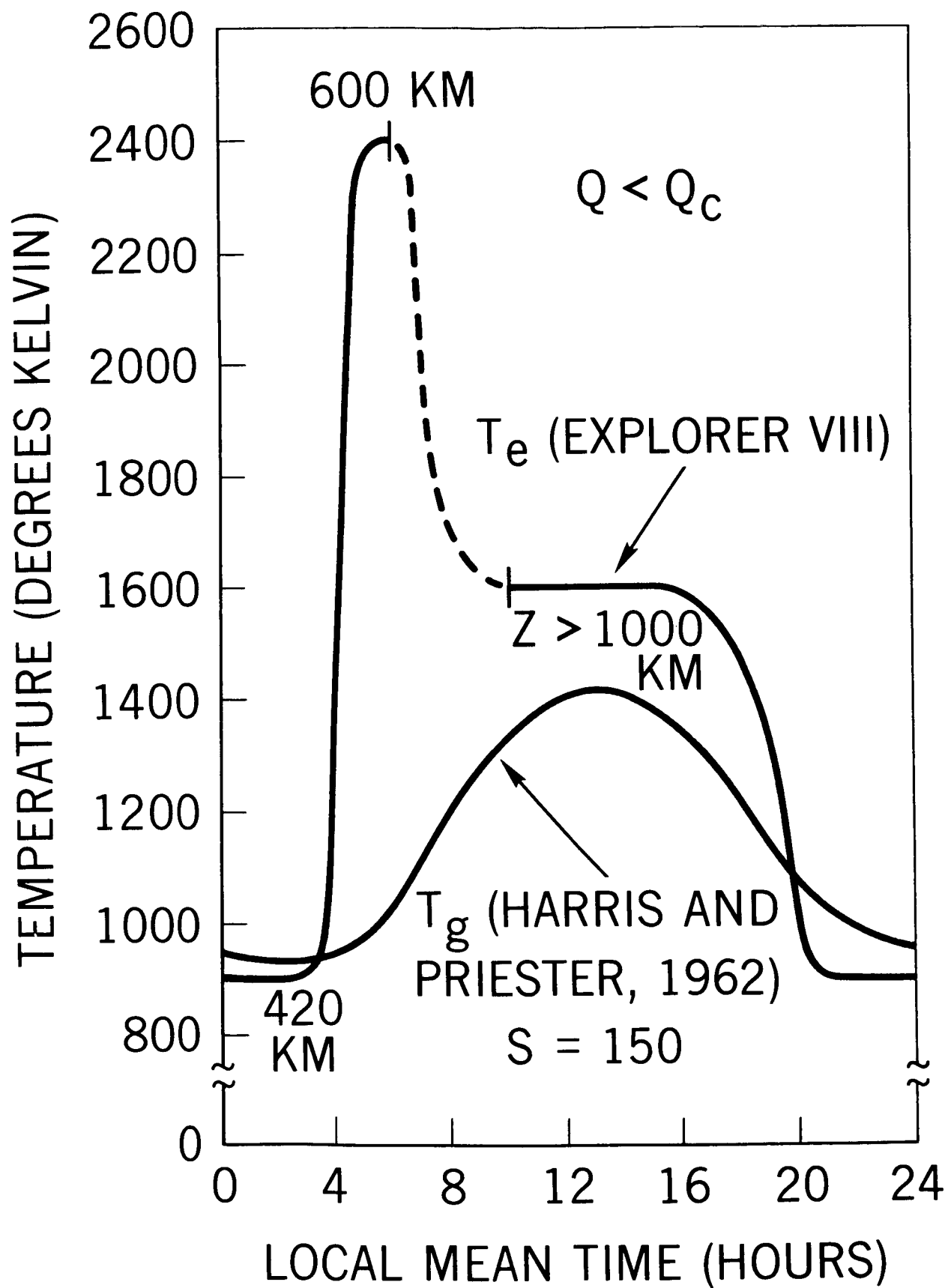
- Aono, Y., K. Hirao and S. Miyazaki, Journ. Rad. Res. Labs. Japan, 9, 407, 1962.
- Aono, Y., K. Hirao and S. Miyazaki, Journ. Rad. Res. Labs., Japan, 8, 453, 1961.
- Bauer, S. J. and Bourdeau, R. E., Journ. Atmos. Sci., 19, 218, 1962.
- Bauer, S. J., Journ. Geophys. Res., 69, 553, 1964.
- Bauer, S. J., and L. J. Blumle, JGR, submitted for publication, 1964.
- Bourdeau, R. E., Space Research II, p. 554, 1961.
- Bourdeau, R. E., Space Sciences Reviews, 1, 683, 1963.
- Bourdeau R. E., and J. L. Donley, Proc. Royal Soc. A., in press, presented May 1963.
- Bourdeau, R. E., J. L. Donley, E. C. Whipple and S. J. Bauer, Journ. Geophys. Res., 67, 467, 1962.
- Bowen, P. J., R. L. F. Boyd, W. J. Raitt and A. P. Willmore, Proc. Royal Soc. A., in press, presented May 1963.
- Bowles, K. L., Ochs, E. R., and Green, J. L., Journ. Natl. Bureau Standards, 66, 395, 1962.
- Bowles, K., XIV General Assembly of URSI, Tokyo, September 1963.
- Brace, L. H., N. W. Spencer, and G. R. Carignan, Journ. Geophys. Res., 68, 5397, 1963.
- Brace L. H., N. W. Spencer and A. Dalgarno, AGU, Washington, April 1964.
- Dalgarno A., McElroy, M. B. and Moffot, R. J., Plan. & Space Sci., 11, 463, 1963.
- Evans, J. V. and M. Loewenthal, URSI, Washington, April 1964.
- Evans, J. V., Journ. Geophys. 67, 4994, 1962.

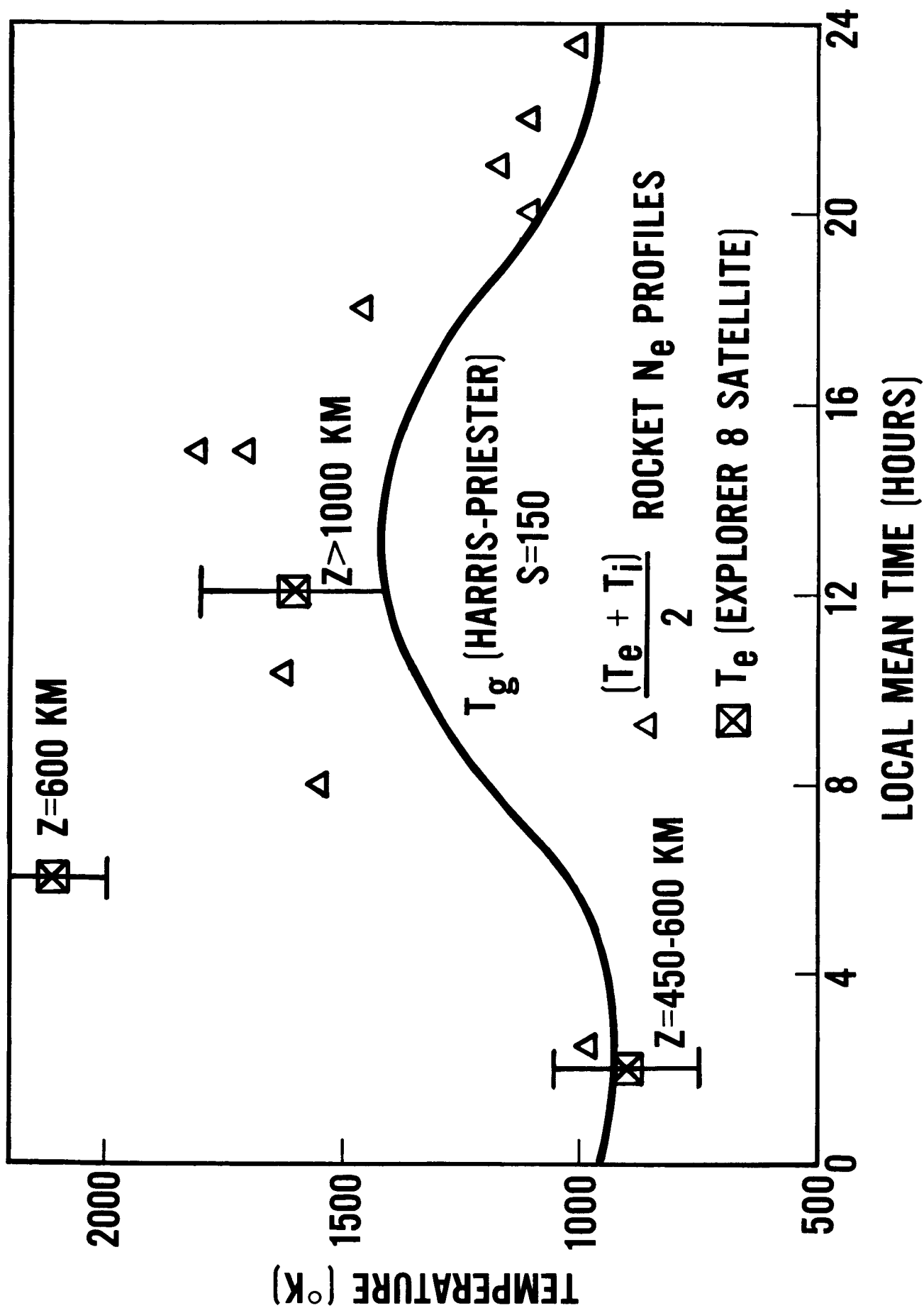
- Gringauz, K. I., B. N. Gorozhankin, N. M. Shutte and G. G. Gdalevich, USSR Geoficicheskaya Sek., 151, 560, 1963.
- Hale, L. C., Journ. Geophys. Res., 66, 1554, 1961.
- Hall, L. A., K. R. Damon and H. E. Hinteregger, Space Research III, 1963.
- Hanson, W. B., Space Research III, p. 282, 1962.
- Hanson, W. B. and F. S. Johnson, Les Congres et Colloques de L'Universite de Liege, 20, 390, 1961.
- Hanson, W. B., Journ. Geophys. Res., 67, 183, 1962b.
- Harris, I., and W. Priester, Space Research III, p. 58, 1962.
- King, J. W., P. A. Smith, D. Eccles and H. Helm, Radio Res. Station, I.M. 94, July 1963.
- Lockwood, G. K. and G. L. Nelms, Journ. Atmos. Terr. Phys. 1964, in press.
- Smith, L. G., Journ. Geophys. Res., 66, 2562, 1961.
- Spencer, N. W., Brace, L. H., and Carignan, G. R., Journ. Geophys. Res., 67, 157, 1962.
- Taylor, H. A., L. H. Brace, H. C. Brinton and C. R. Smith, Journ. Geophys. Res., 68, 539, 1963.
- Willmore, A. P., C. L. Henderson, R. L. F. Boyd and P. J. Bowen, Proc. Royal Soc. A., in press, presented May 1963.
- Willmore, A. P., Proc. Royal Soc. A., in press.
- Wright, J. W., NBS Technical Note, 138, 1962.

# FIGURE CAPTIONS

- Figure 1. Typical winter mid-latitude electron density profiles.
- Figure 2. Diurnal electron temperature variation measured during November 1960 from the Explorer VIII Satellite for magnetically-quiet days at mid-latitudes assuming  $T_e$  is constant with altitude (425-2400 KM).
- Figure 3. Early charged particle temperature measurements in the upper ionosphere.
- Figure 4. Scale heights at 500 km from Alouette Satellite data (Bauer-Blumle, 1964).
- Figure 5. Idealized representation of equatorial anomaly along 75°W meridian based upon data by Lockwood and Nelms (Topside) and J. W. Wright (Bottomside).

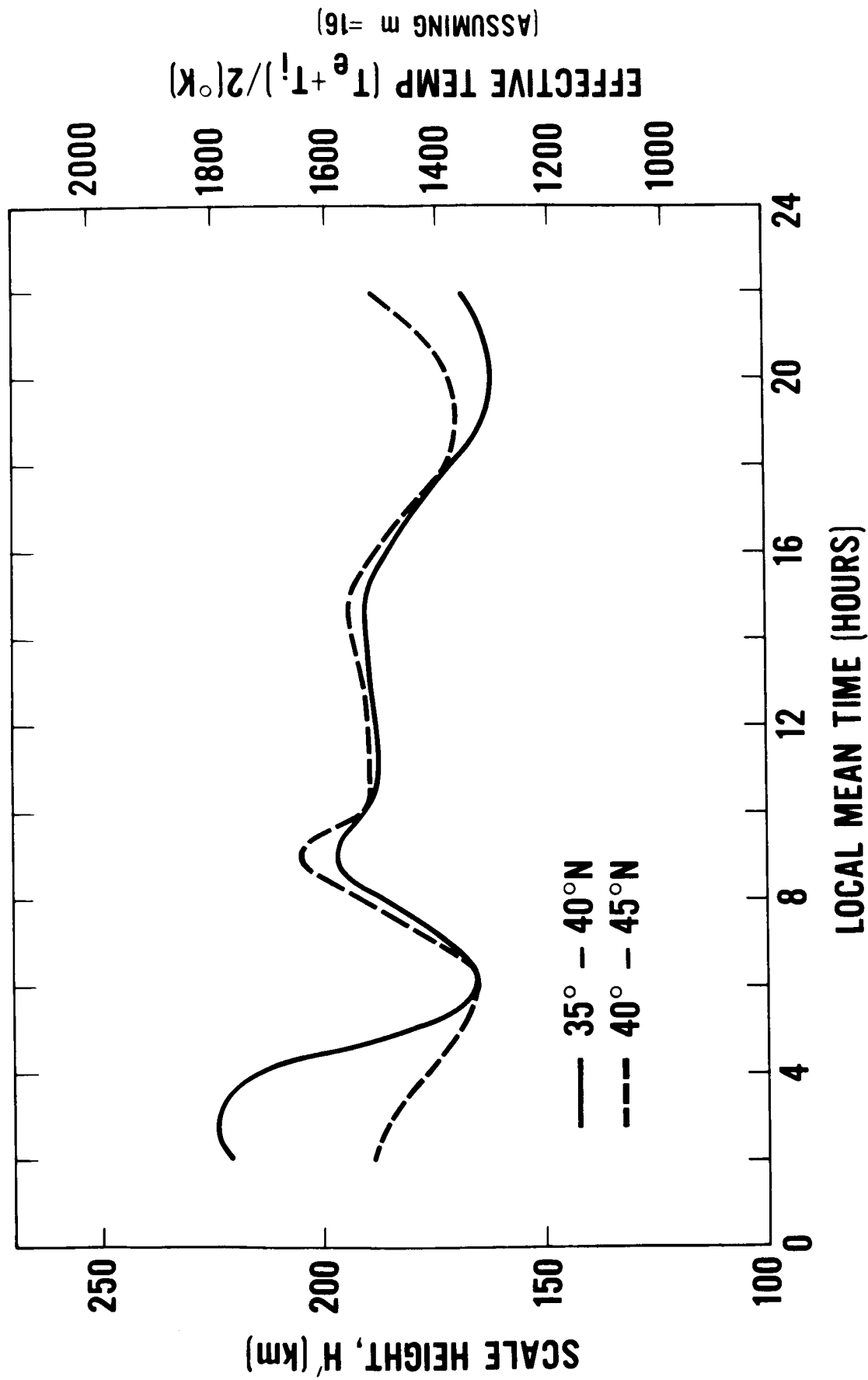


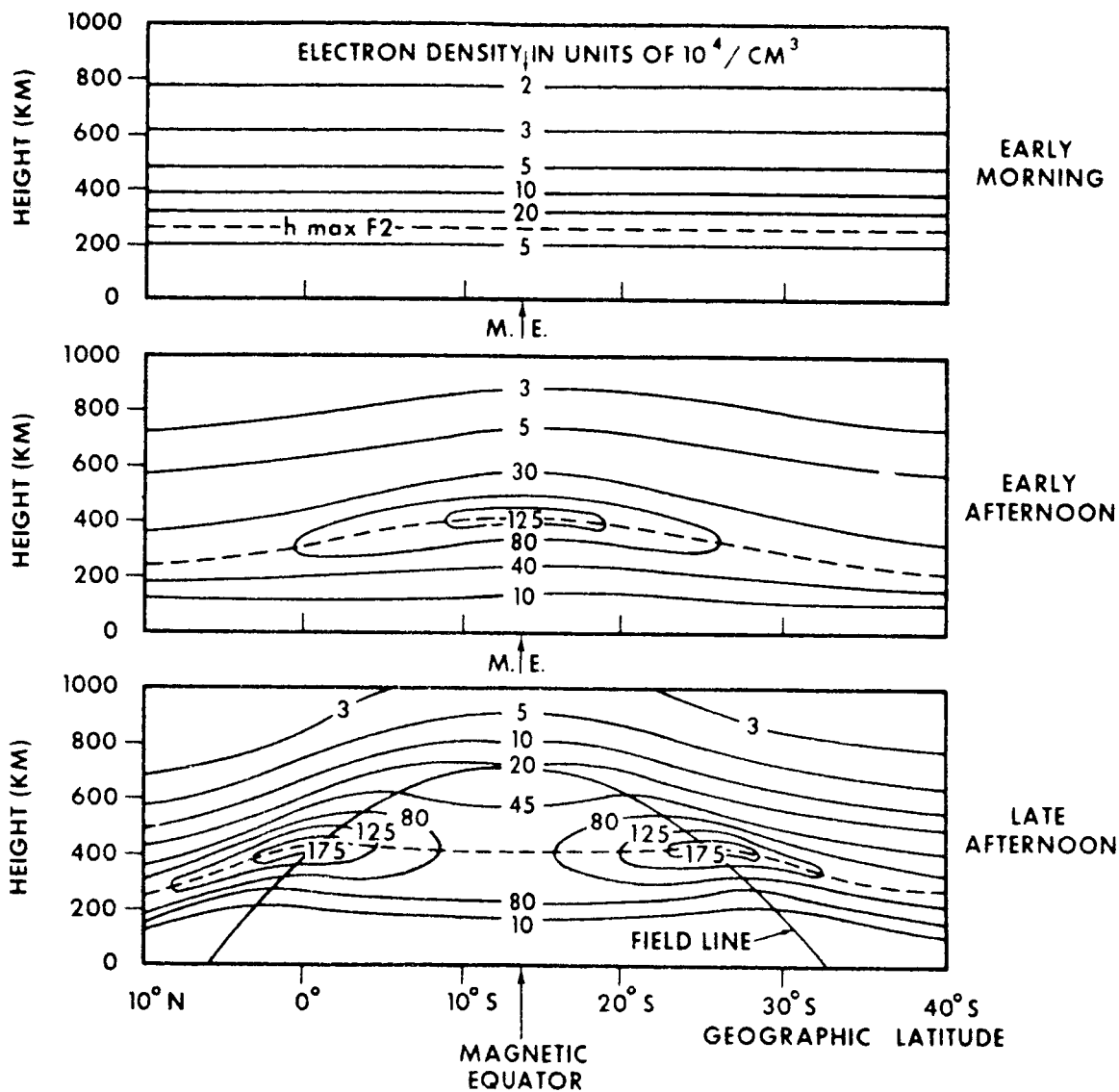






# SCALE HEIGHTS AT 500 KM FROM ALOUETTE SATELLITE DATA (BAUER - BLUMLE, 1964)





IDEALIZED REPRESENTATION OF EQUATORIAL ANOMALY ALONG 75°W MERIDIAN  
 BASED UPON DATA BY LOCKWOOD & NELMS (TOPSIDE) AND J.W.WRIGHT (BOTTOMSIDE)

— SYMMETRY OF CONTOURS IMPLY EQUINOCTIAL CONDITIONS —